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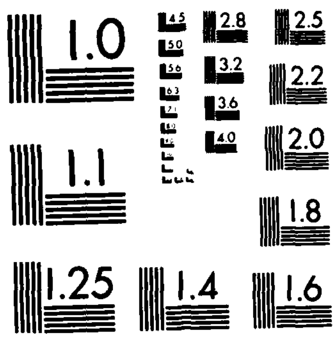

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FUNDAMENTAL STUDIES RELATED TO FAILURE OF ADHESIVELY BONDED STRUCTURES

by

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1. INTRODUCTION

The success of using adhesively bonded structures hinges to a large degree on one's ability to reliably predict the durability of bonded parts in service. In virtually all circumstances bonds are used to transmit mechanical forces from one of the adherends to the other. The flow of force thus passes via the interfaces of the adherends from one to the other. Clearly the interface is thus a critical domain in any bond. For this reason most attention has been focussed on this region in the past in a continuous effort to improve the "strength of bonds" through better adhesion and surface preparation characteristics.

This kind ~~of~~ effort ~~has occurred~~ much ~~without~~ attent~~ion~~ to the mechanical deformations which accompany the failure process~~es~~. Even less attention has been paid to the deformations that accompany the generation of an adhesive bond in the form of "residual" stresses. These more mechanics-based concerns are of dominant importance in the proper design and durability evaluations that are so important in judging the viability of adhesive bond technology and application.

It is with these considerations in mind that we embarked on the current research effort. There are many mechanics-related issues that need clarification. However, there are only limited amounts of time and funds to accomplish these objectives and therefore we restrict ourselves at this time to those objectives which are primary input into a mechanics-based analysis of adhesive bond failure.

The problems which ~~we~~ perceive to ~~be~~ important in this connection are a) the proper design and evaluation of tests; and b) the careful characterization of the materials

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and interfaces involved in the bond. We shall consider these topics in turn below. However, it is appropriate to indicate here already that under the second category of material and interface characteristics the issues of linear versus non-linear material behavior is important, a question in which the scrim material tends to play a major role. Moreover, the question of the role of material gradients in the adhesive or, more specifically in the interphase is of concern for understanding. Lastly, we shall report on efforts to perform careful material properties measurements.

2. UNDERSTANDING AND ANALYZING TEST PROCEDURES

Testing is involved in both materials characterization and in the determination of failure characteristics. It has become common to associate certain types of tests with certain properties and failure characteristics. For example the uniaxial tension test is usually associated with modulus and some failure characterization. The peel test is used to gage adhesion and the DCB test is often used to identify and quantify joint failure. However, invariably the test evaluation is based on the linearized theory of elasticity or viscoelasticity. This limitation may be severe and it is therefore important to better understand their impact.

For this reason we have embarked on an analytical examination of the DCB test in light of non-linear material behavior. This investigation was conducted in conjunction with another program (NASA) which has related objectives. It was of special interest to examine the response of the DCB measurements to non-linear material

behavior of the adhesive. The question was oriented to illuminate both the deformation as well as the fracture response of the test geometry. More precisely, it was of interest in connection with the deformation response to examine whether the non-linear material characteristics of the adhesive at the front of the crack in the interlayer can be determined from measurements on the deformed adherends.

The answer to this question appears to be a "yes": Measurements with optical interferometry should be sensitive enough to determine the most important non-linear characteristics of the adhesive as it approaches failure in the joint. These findings are now being combined with the effort on non-linear material behavior as described below.

3. MATERIAL CHARACTERIZATION

As mentioned before there are needs to characterize the material behavior with respect to both deformation and failure response. In this endeavor we are concerned with both the standard material tests as well as with the phenomenon of how possible material gradients along the interface can affect the deformation and fracture behavior.

3.1 Effect of Scrim Cloth

The main purpose of scrim cloth in adhesives is their role in handling and in the control of bondline thickness. When adhesives are evaluated in their neat form -which is often done with scrim cloth present- the scrim is mostly neglected. More specifically, when deformations and failure of test joints are considered the effect of scrim on the

measurements are usually not taken into account. The reason is, of course, that the scrim is an integral part of the adhesive and therefore should not warrant separate consideration.

A simple example shows that this argumentation is not universally valid: When the "modulus of elasticity" of the adhesive is measured, it is done usually so that the scrim cloth is aligned with the tension in the specimen. However, when the adhesive is used the scrim cloth is aligned normal to the line of tension or at some angle (under bond shear). In the (numerical) analysis of the joint this fact is never considered and the properties determined in a simple tensile coupon are usually employed without regard to the possible anisotropy in the adhesive.

For this reason we have embarked on measuring the stiffnes of adhesive normal to the scrim plane. We have started to do this first by constructing simple tensile coupons with the dimensions as shown in Figure 1. A photograph of such a coupon is shown in Figure 2. The coupons are manufactured in a mold so that setting occurs under pressure. The specimen is generated by laying up approximately 150 layers of scrimmed material. For comparison purposes we also generate specimens of unsrimmed material. At present we are working with a 3-M AF163 2M scrimmed and AF163 2U unscrimmed adhesives. We have also ordered now srimmed and unscrimmed FM73 from Cyanamid. Because we are dealing with small quantities we are dependent on the good will of the suppliers and the order time is surprisingly long.

At this time we attempt to measure the strain in these coupons by adhering strain gages to the test section. The main problem we have encountered so far is that the total

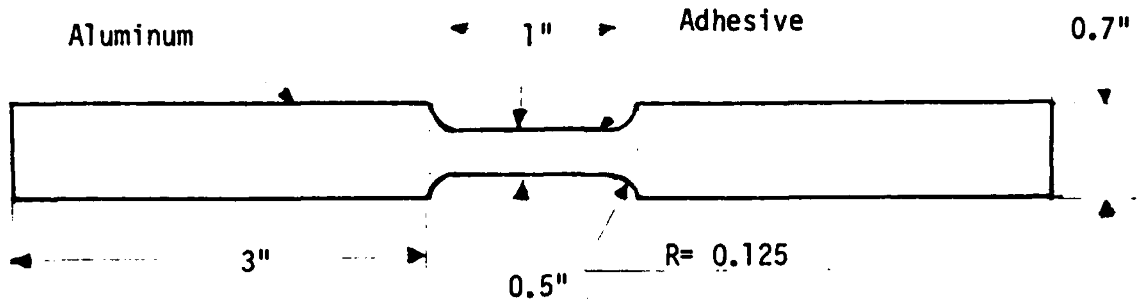

Figure 1.

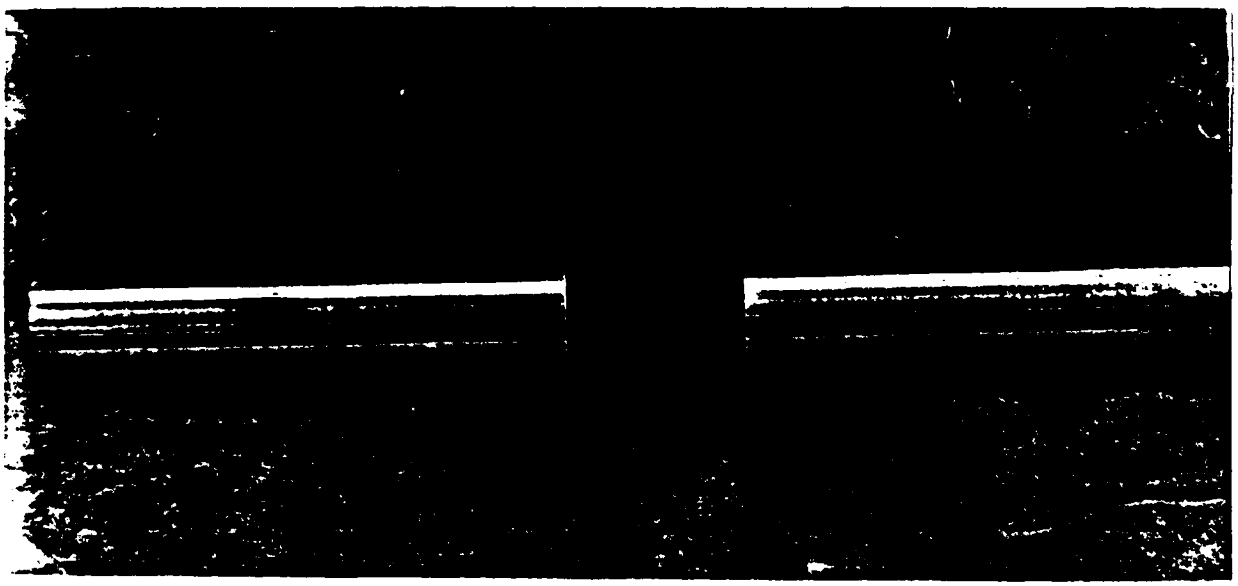

Figure 2.

elongation is rather small and significant uncertainty results in the data. We are now investigating whether that small strain capability is the direct consequence of the scrim cloth or not. The unscrimmed material has a tendency to develop voids, a problem with which we are presently trying to cope.

3.2 Effect of scrim in a DCB Specimen

An alternate method to determine the effect of the scrim cloth on the modulus is to test a DCB specimen and to infer from the detailed measurements the modulus response. With the analysis performed in connection with the work under section 2. we are able to assess the deformation of the adherends in detail if we use optical interferometry to determine the deformations of the adherends. In parallel to the tensile coupons we are presently exploring that possibility by making specimens of reasonable thickness and attempting to polish them to optical quality. The specimen intended for this study is shown dimensioned in Figure 3 and a photograph of a completed specimen ready test in Figure 4.

3.3 Effect of Gradients on Fracture Path

It has been recorded many times in the literature that so-called interface fracture really follows a path that is removed a small distance from the true interface or interphase and passes through the adhesive. This behavior has always been a puzzle to many investigators because it is not readily understood in terms of the normal surface physics phenomena. We believe that the source for this behavior is purely mechanical and a direct consequence of the nonlinear material behavior of the adhesive.

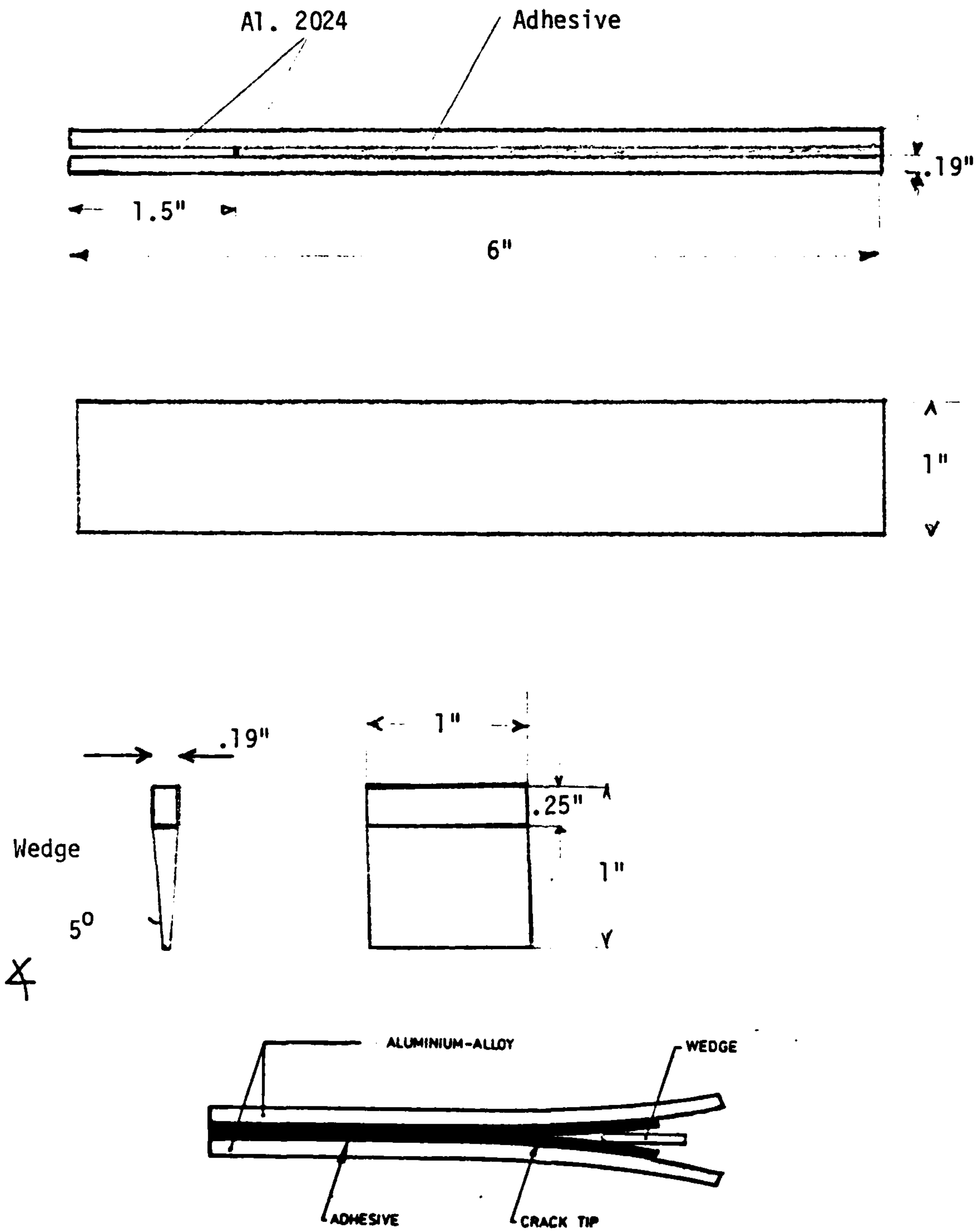
Al. 2024
Adhesive
.19"
1.5"
6"
1"
.19"
1"
Wedge
.25"
5°
1"
4
ALUMINIUM-ALLOY
WEDGE
ADHESIVE
CRACK TIP

Figure 3.

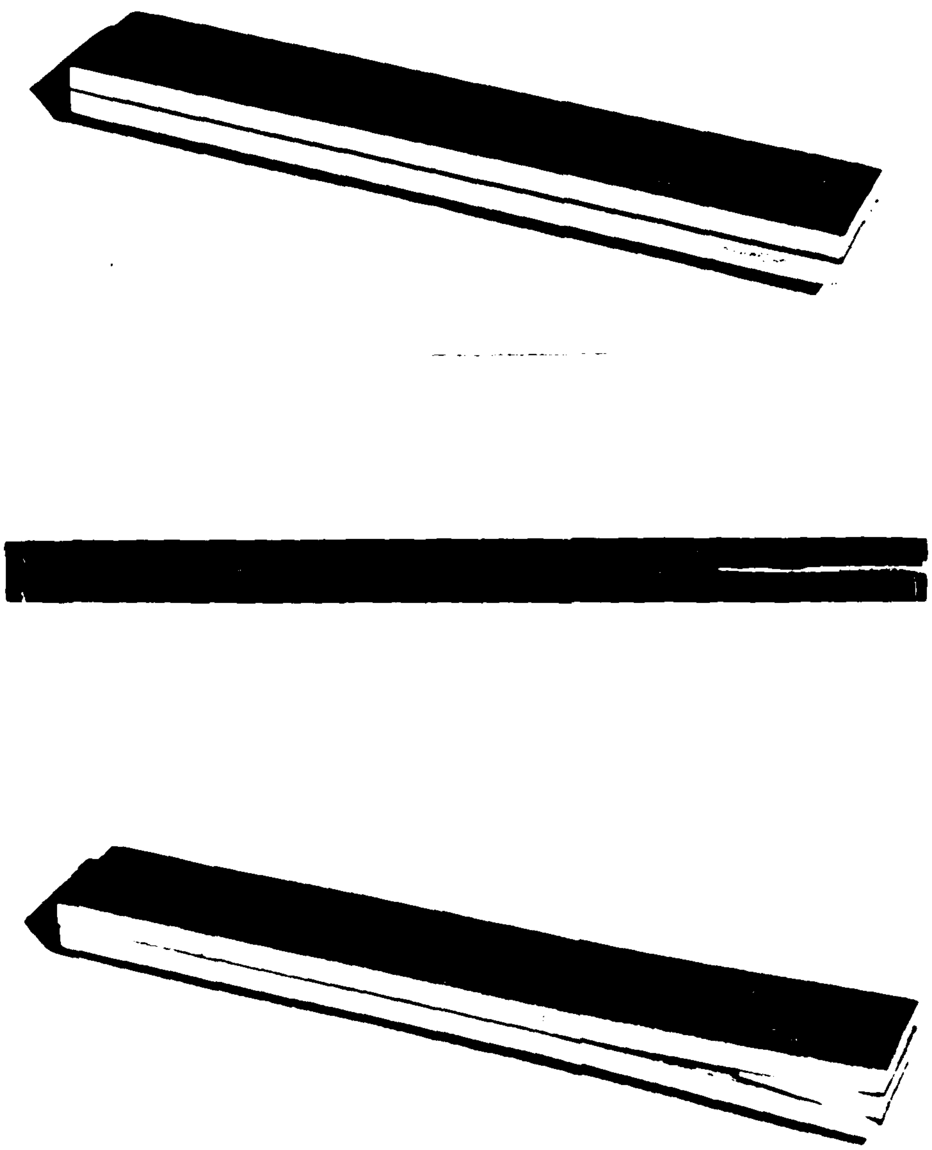

Figure 4.

Preliminary planning has led to making material with property gradients in them and then propagate a crack through the gradient. We have explored the formation of such gradients in our own laboratory through casting polyurethane materials of different formulations against each other. In this mode it is not very certain what the precise property gradients are. We are exploring different methods, involving diffusion of one compound into the other one at various stages of cure. A difficulty confronting us is the lack of tools by which we can quantify the property gradients.

In considering this experimental approach in some detail it occurred to us that the fracture in the vicinity of a relatively rigid interface must be strongly influenced by the non-linear strain filed at the tip of the crack and the latter's interaction with the rigid boundary. This problem can be studied experimentally or analytically.

The experimental approach would be to generate adhesives with different non-linear material characteristics, so that this interaction can be studied in a series of different adhesives. The initial problem with that approach is that when different materials are employed one would, in all likelihood also change the fracture characteristics of the adhesive and thus not be certain of whether any observed experimental trends are due to the non-linear material behavior or due to the difference in the fracture toughness.

For this reason it appears more prudent to study this problem first analytically so as to understand the idealized effect of the non-linear material behavior. Accordingly we are, in conjunction with another program on

the non-linear processes of crack tip behavior, embarking on the proper treatment of non-simple material behavior in connection with crack tip response to high stresses. We expect that this problem will come under direct attack some time this summer after the initial formulation of the numerical problem class is completed.

3.4 Small Strain Deformation Response

One of the most important viscoelastic response characteristics of a polymer is its relaxation or creep behavior. This statement is true whether one is concerned with affine deformations or with large strains. It is generally believed that the small strain viscoelastic properties are also indicative of those that occur under large strains, although the connection is, in general, not well understood. We, therefore, are certain that any serious adhesive program must pay attention to the classical viscoelastic behavior.

Accordingly, we have largely resurrected and refurbished a creep torsiometer which had been built over ten years ago out of carbon steel. The torsiometer is configured to have all moving part run on air bearings for minimal energy loss to friction. The torsiometer works well, but has developed rust problems. We are therefore rebuilding the instrument with stainless steel parts, and that work is almost complete. The instrument is housed in a temperature controll enclosure for easy thermoviscoelastic evaluations.

4. MANPOWER

The researcher primarily responsible for the experimental work on adhesion specimens is Mr. Mordechai Sobel. Mr. Sobel is on leave of absense from the Israeli Weapons Establishment where his primary responsibility is in adhesion technology. He is presently spending about 50% of his time on this project.

A graduate student, P. Washabaugh, has been responsible for reworking the torsiometer. His time for this project has been underwritten in the form of a teaching assistantship by the Institute, so that only costs on hardware have accrued to the program.

5. FUTURE WORK

It is planned to continue with the evaluation of the effect of scrim cloth on the modulus of adhesive ~otropic properties); both the standard coupon approach as well as the more time-consuming optical interferometry technique are being pursued.

The torsiometer refurbishing will be completed soon, so that measurements of typical adhesives can be pursued this summer.

Finally, the numerical work on the analytical study of the near-adherend fracture will be attempted. The computer program for this task is in hand for smaller problems; the code for time-efficient solutions of larger problems has been promised for the month of April, after the original promise was for October last year. We have already studied some

aspects of the non-linear problem without the special case of a crack-near boundary. The special problem discussed here should thus be an extension of that earlier work.